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DISCOVERY OF A "TRANSIENT MAGNETAR:" XTE J1810–197

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ABSTRACT

We report the discovery of a new X-ray pulsar, XTE J1810–197, that was serendipitously discovered on 2003 July 15 by the *Rossi X-ray Timing Explorer (RXTE)* while observing the soft gamma repeater SGR 1806–20. The pulsar has a 5.54 s spin-period and a soft X-ray spectrum (photon index ≈ 4). We detect the source in earlier *RXTE* observations back to 2003 January. These show that a transient outburst began between 2002 November 17 and 2003 January 23 and that the pulsar has been spinning down since then with a high rate $\dot{P} \approx 10^{-11}$ s s^{-1} and no evidence for Doppler shifts due to a binary companion. No SGR-like bursts were detected from the source. The rapid spin-down rate and slow spin-period imply a super-critical characteristic magnetic field $B = 3 \times 10^{14}$ G and a young age $\tau \leq 7600$ yr. Follow-up *Chandra* observations provided an accurate position of the source within its error radius the 1.5 m *Russian-Turkish* Optical Telescope *RTT150* found a limiting magnitude $R_c = 21.5$. All these properties are strikingly similar to those of anomalous X-ray pulsars and soft gamma repeaters, providing strong evidence that the source is a new magnetar. Archival *ASCA* and *ROSAT* observations show a point source consistent with XTE J1810–197 but nearly two orders of magnitude fainter. This makes XTE J1810–197 the first confirmed transient magnetar and suggests that other neutron stars sharing the properties of XTE J1810–197 during its inactive phase may be unidentified transient magnetars awaiting detection via a similar activity.

Subject headings: Pulsar: Individual (XTE J1810–197) — Stars: Magnetic Fields — Stars: Neutron — Stars: Magnetar — X-Rays: Bursts

1. INTRODUCTION

Among several hundred X-ray pulsars known to date, a dozen objects are quite distinct and least understood. These are the soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). They rotate relatively slowly with spin periods in the narrow range $P \sim 5-12$ s and spin-down rather rapidly at $\dot{P} \sim 10^{-11}$ s s^{-1}. Both are radio-quiet, persistent X-ray sources ($L \sim 10^{34}-10^{36}$ erg s^{-1}) with the unique property of sporadic emission of short (< 0.1 s), super-bright ($L_{peak} > L_{EDD}$) bursts of X-rays and soft γ–rays. No evidence has been found for a binary companion or a remnant accretion disk to power their emission, although it is more than an order of magnitude higher than can be provided by their rotational energy. Nine sources are currently firmly identified, including four SGRs and and five AXPs (See Hurley 2000 and Mereghetti et al. 2002). Four more candidates need confirmation.

The magnetar model provides a coherent picture in which SGRs and AXPs radiation is powered by a decaying super-critical magnetic field, in excess of the quantum critical field $B_c = 4.4 \times 10^{13}$ G (Duncan & Thompson 1992; Thompson & Duncan 1995). Evidence for magnetars has come from the energetic burst emission (Paczynski 1992; Hurley et al. 1999; Ibrahim et al 2001), the long spin-period and high spin-down rate (Kouveliotou et al. 1998; 1999; Vasisht & Gotthelf 1997), and the lack of binary companion or accretion disks (Kaplan et al. 2001). Further evidence has recently come from spectral line features that are consistent with proton cyclotron resonance in $B \simeq 10^{15}$ G field (Ibrahim et al. 2002; Ibrahim, Swank & Parke 2003). Until recently only SGRs were observed to burst. The recent bursting activity from two AXPs has unified the two families of objects in the magnetar framework and made them less differentiated (Gavriil, Kaspi & Woods 2002; Kaspi et al. 2003).

Here we present the discovery of a new transient X-ray pulsar whose properties are remarkably consistent with those of AXPs and SGRs. We discuss the implications of this finding to our understanding of the characteristics and population of magnetars.

2. OBSERVATIONS AND RESULTS

2.1. *A New X-ray Pulsar Near SGR 1806–20*

Following the *Interplanetary Network (IPN)* report of renewed burst activity from SGR 1806–20 on 2003 July 14 (Hurley et al. 2003), we observed the source on July 15 with the Proportional Counter Array (PCA) onboard *RXTE*. PCA data in the event-mode configuration `E_125US_64M_0_1S` were collected from all layers of the operating PCUs (0, 2 & 3) in the 2–8 keV band, corrected to the solar system barycenter, and binned in 0.125 s intervals. A strong periodic signal with a barycentric period of 5.540(2) s at a chance probability of 2.5×10^{-12} was clearly identified in the first observation, which lasted for only 2.6 ks (Ibrahim et al. 2003; see Fig. 1). The large discrepancy between this pulse period and the expected

7.5 s pulse period of SGR 1806–20 implied the presence of a new X-ray pulsar in the PCA $1^\circ.2$ field of view.

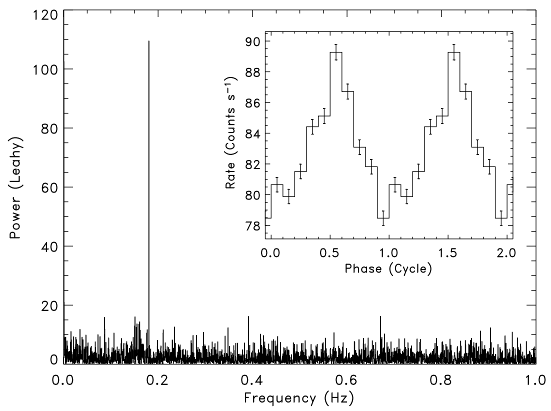

FIG. 1.— Fast Fourier Transform power spectrum of the *RXTE* PCA July 15 observation of the field of view of SGR 1806–20 showing a highly significant periodic signal at 0.18052(6) Hz. The inset shows the epoch folded pulse profile in 10 phase bins. Errors in the frequency and period correspond to the 3σ confidence level. Note that the ≈ 0.13 Hz signal due to SGR 1806–20 is not detected here, indicating a low pulsed flux. Subsequent observations confirmed this.

2.2. *Source Position and Optical Counterpart*

A PCA scanning observation was performed on July 18, following a path that covered a region surrounding SGR 1806–20. During scans, the count rates due to individual sources are modulated by the response of the PCA collimator. The resulting light curves are corrected for internal background (using the "CM" L7 background model), and are fitted to a model of known and unknown sources, convolved with the collimator response. For unknown sources, a trial position is assumed and adjusted until the best fit is achieved. The sources included in this fit were the new source, SGR 1806–20, the galactic ridge, and an overall diffuse level. The uncertain spatial distribution of the galactic ridge emission in the field of view was modeled as an unresolved ridge at 0° latitude. The best fit position and 3σ contour obtained for the position of the new source, designated XTE J1810–197, are shown in Fig. 2 (Markwardt, Ibrahim & Swank 2003).

Two follow-up *Chandra* observations with the High Resolution Camera (HRC) on August 27 and November 1 localized the source precisely to $\alpha = 18^{\rm h}09^{\rm m}51^{\rm s}.08$ and $\delta = -19^\circ 43' 51''.74$ (J2000), with an error circle radius of $0''.8$ (Gotthelf et al. 2003a; 2003b; Israel et al. 2003). Pulsations in the HRC data definitively identified the source. The HRC position is $14'$ from the best fit PCA position. Typically, accuracies of 1–$2'$ have been obtained in past scans for bright sources. The presence of the diffuse galactic ridge and other, un-modeled, faint sources in the field of view — in particular SNR G11.2–0.3 — resulted in large systematic errors, for which a priori estimates were difficult.

We observed the first *Chandra* HRC error box with the 1.5 m *Russian – Turkish* Telescope, *RTT*150 (Antalya, Turkey) on 2003 September 3 and 6. Optical Cousins R filter images of the field around the source were obtained using the ANDOR CCD (2048×2048 pixels, $0.24''$ pixel scale and $8' \times 8'$ Field of View) with 15 min exposure times (3 frames). Seeing was about $2''$. We did not detect a counterpart to a limiting magnitude of 21.5 (2σ level) in the R_c band, comparable to the limits in V(22.5), I(21.3), J(18.9), and K(17.5) obtained by Gotthelf et al. (2003b). Recently, Israel et al. (2003) reported a likely IR counterpart with $K_s = 20.8$ and $F_X/F_{IR} > 10^3$.

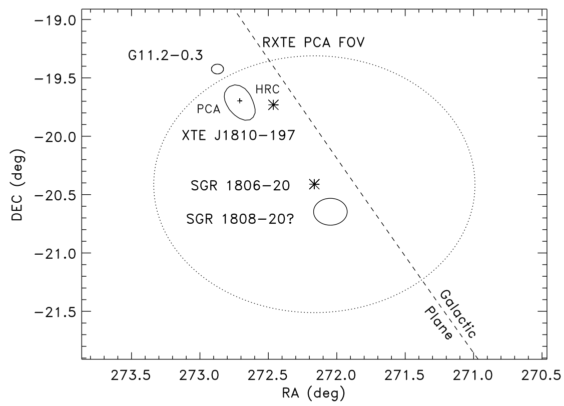

FIG. 2.— The PCA field of view during the SGR 1806–20 pointed observation, showing the neighborhood of SGR 1806–20, including XTE J1810–197, the supernova remnant G11.2-0.3 that contains the 65 ms pulsar PSR J1811–1925, and the potential SGR 1808–20 (Lamb et al. 2003). The positions of XTE J1810–197 from the PCA scan and HRC observations are indicated. Also shown is the 3σ PCA error contour, with semi-major axes of $5.5'$ and $10'$.

2.3. *Long Term Light Curve: A Transient Source*

XTE J1810–197 appeared consistent with a previously unidentified source that had been present in the PCA monitoring program of the galactic bulge region since 2003 February. A region of approximately 250 square degrees around the galactic center has been scanned by the PCA twice weekly since 1999 February, except for several months per year, when sun and operation constraints interfere. The scan pattern is a zig-zag which alternates semi-weekly between primarily north-south and east-west. XTE J1810–197 is covered in the north-south scans only. At the end points of each scan the PCA dwells for ≈ 150 seconds, and XTE J1810–197 is near the center of the PCA field of view of one of these points. Re-examining the data during these brief points revealed the pulsations, which confirmed the identification of the source.

Fig. 3 shows the 2002–2003 light curve of XTE J1810–197 from the bulge scan measurements, when fixed at the *Chandra* position. The scans are the only set of PCA observations that can consistently resolve the contributions of the source and diffuse background. Clearly XTE J1810–197 became active sometime between 2002 November and 2003 February. The distribution of 1999–2002 pre-outburst fluxes allow us to place a 3σ upper limit on previous outbursts of < 2 ct/s/PCU or 1 mCrab (2–10 keV) from the baseline level, as long as the outburst did not fall in an observing gap (the maximum gap was 3 months).

The flux decay can be fitted to power-law or exponential models. For the exponential model, the e-folding time is 269 ± 25 days. The power-law model has the potential of retrieving the epoch at which the outburst began. Assuming the flux is proportional to $((T - T_0)/(52700 - T_0))^{-\beta}$, at time T and with outburst time T_0 in MJD, $\beta = 0.45 - 0.73$ were acceptable (1σ), with $52580 \le T_0 \le 52640$, that is, 2002 November 2 to 2003 January 1. Additional information came from observations of the nearby PSR J1811–1925 that had XTE J1810–197 in the field of view (Obsids 70091-01, 80091-01). An observation on 2002 November 17 (MJD 52595) showed that the pulsations were not detected, while they were by 2003 January 23 (MJD 52662).

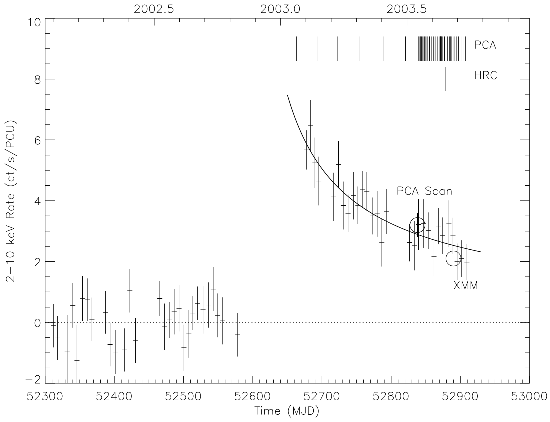

FIG. 3.— Monitoring light curve of XTE J1810–197, showing the transient outburst beginning in 2003 (1 mCrab = 2.27 ct/s/PCU = 2.4×10^{-11} erg cm^{-2} s^{-1}, 2–10 keV). We have subtracted from the rate an offset of 0.68 ct s^{-1} PCU^{-1}, which we ascribe to diffuse and unresolved emission in the region and not accounted for by our model. Epochs of PCA dedicated pointed observations with the source in the field of view are indicated in the top row of vertical bars. The epoch of the first HRC pointing is shown separately. The flux from the *XMM-Newton* spectrum (§ 2.4), converted to an approximate PCA flux using the PIMMS simulator, is shown as the lower circle. The upper circle is the flux derived from the dedicated PCA scan.

2.4. *Spectrum*

A PCA spectrum was estimated by reanalyzing the July 18 light curves in each spectral band, this time using the *Chandra* position and allowing a contribution from G11.2–0.3 (Markwardt, Ibrahim,& Swank 2003). The resulting spectrum of XTE J1810–197 was clearly soft, despite large uncertainty in the column densities for any model. For the column fixed at 1×10^{22} cm^{-2} (typical for sources in the region and subsequently measured to be the case by *XMM-Newton*), a power-law fit has a photon index $\Gamma = 4.7 \pm 0.6$, with a 2–10 keV absorbed flux was 5.5×10^{-11} ergs cm^2 s^{-1}. Additional PCA spectral data requiring analysis beyond the scope of this paper will address spectral evolution during the outburst and be presented elsewhere.

The source was observed with *XMM-Newton* on 2003 September 8. Our results with EPIC PN and MOS1 together confirm those reported by Tiengo & Mereghetti (2003) and by Gotthelf et al. (2003b) with EPIC PN. A two-component power-law plus blackbody model gave a good fit, with well constrained 3σ parameters of $\Gamma = 3.75(3.5-4.1)$, $kT = 0.668(0.657-0.678)$ keV, $n_H = 1.05(1.0-1.13) \times 10^{22}$ cm^{-2}, and $\chi^2_\nu = 1.04$ (ν=896). The total unabsorbed flux in 0.5–8.0 keV is 1.35×10^{-10} erg cm^{-2} s^{-1} for a source luminosity of $1.6 \times 10^{36} d_{10}^2$ erg s^{-1}, with d_{10} the distance in units of 10 kpc.

The HRC position is consistent with a point source seen in archival *ROSAT* and *ASCA* observations during 1993-1999 (Bamba et al. 2003). The source was in a faint state with a much softer spectrum ($kT \approx 0.15$ keV) and unabsorbed luminosity of $5.9 \times 10^{34} d_{10}^2$ erg s^{-1} (see also Gotthelf et al. 2003b).

2.5. *Timing: Frequency History and Spin-down Rate*

Our timing analysis used a variety of PCA observations, including pointed observations dedicated to XTE J1810–197 (Obsid 80150-06) observations of G11.2-0.3 and PSR J1811–1925, SGR 1806–20 (Obsids 80149-02, 80150-01), plus the bulge scans (Obsids 80106, 70138). The total exposure time was about 216 ks between 2003 January 23 and September 25. Folded light curves were extracted (2–7 keV; top PCU layers) based on a trial folding period. A sinusoidal profile fit well, and was used to estimate the pulse times of arrival (TOAs) and uncertainties. By using a combination of all data sets we were able to extend a phase connected solution through the complete time span. While we attempted several models, a polynomial is commonly used.

TABLE 1

POLYNOMIAL SPIN PARAMETERS

Parameter	Jan 23–Sep 25	Jul 13–Sep 25
MJD range	52,662.9 – 52,907.3	52,833.4 – 52,907.3
Epoch (MJD)	52,788.0	52,788.0
χ^2/dof	1258 / 100	193 / 62
ν (Hz)	0.180530831(4)	0.180530266(1)
$\dot\nu$ (10^{-13} Hz s^{-1})	-6.72(2)	-3.765(2)
$\ddot\nu$ (10^{-20} Hz s^{-2})	9.0(2)	
$\nu^{(3)}$ (10^{-27} Hz s^{-3})	9.9(4)	
$\nu^{(4)}$ (10^{-32} Hz s^{-4})	-1.65(6)	
$\nu^{(5)}$ (10^{-40} Hz s^{-5})	-2.9(8)	
$\nu^{(6)}$ (10^{-45} Hz s^{-6})	2.5(1)	

Note– Errors were determined with χ^2 normalized to dof.

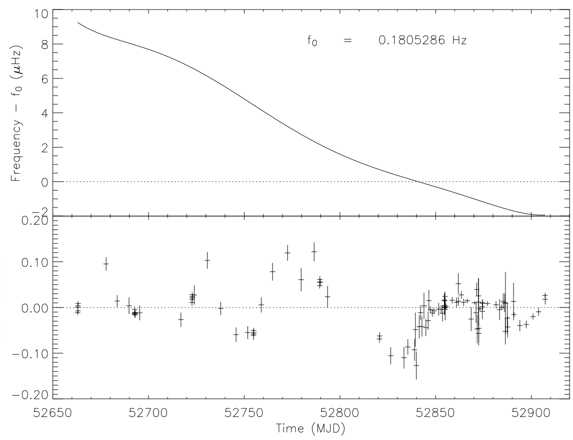

FIG. 4.— (top) Frequency evolution and (bottom) phase residuals for PCA timing solution of XTE J1810–197.

Fig 4. shows the frequency evolution and phase residuals for the polynomial fit with frequency and 6 derivatives (see Table 1 for parameters). While the choice of polynomial order is somewhat arbitrary, a lower order produces significantly worse residuals. The weighted RMS residuals are 165 ms. Reminiscent of the behavior of 1E 2259+586 after a bursting episode (Kaspi et al. 2003), the spin down is initially steeper, but evolves to a quieter and slower rate. The weighted RMS deviation since July is only 94 ms for a steady spin-down (i.e. 2nd order polynomial; Table 1). The mean pulse period derivative is 1.8×10^{-11} s s^{-1} over the full time span of the data, and 1.15×10^{-11} s s^{-1} for the July–September time span.

With 245 days of data, it is possible to rule out a long period orbit (≥ 100 days) as entirely responsible for the frequency slow down (Markwardt et al. 2003). While a phase-connected solution is possible for an orbit *plus* a spin-down, such models are dominated by the spin-down component (best fit $\dot\nu = -5.4 \times 10^{-13}$ Hz s^{-1} for a mildly eccentric orbit with a period of 232 days; compare to Table 1).

To look for short period orbits we made Lomb-Scargle periodograms of the phase residuals obtained from subtracting the polynomial model. They show no significant peaks at the 95%

confidence level. For orbital periods down to 20 minutes, the peak periodogram power was 21, for a maximum orbital amplitude, $a_x \sin i$, of 70 lt-ms. Such a limit is independently inferred from the high stability of the spin-down rate during the past 80 days. This would imply a mass function of $4\times10^{-7}M_\odot/P_d^2$, P_d being the binary period in days. Thus, except for orbits improbably close to face-on, a companion mass would be restricted to be planetary in size.

3. DISCUSSION

The nature of a neutron star source is principally determined by the energy mechanism that powers its emission. The rotational energy loss due to the pulsar spin-down[1], $\dot{E} \approx 4\times10^{33}$ erg s^{-1}, is at least 50 times lower than the implied *XMM* unabsorbed luminosity. From § 2.4, $L_X = (2-16)\times10^{35}$ ergs s^{-1}, assuming $d_{10} = 0.3-1$. The distance to XTE J1810–197 is almost certainly in that range (from inferred n_H), and most likely ~ 5 kpc (Gotthelf et al. 2003b). L_X is notably in the range of AXP and SGR luminosities. A binary system is unlikely since a Doppler shift can not explain the observed frequency trend and there are strong limits on the mass of any companion in a short period orbit (§ 2.5). The spectrum of the source is significantly softer than typically hard spectra of high mass X-ray binaries. Besides, the optical and infrared magnitudes (§ 2.2; Gotthelf et al. 2003b; Israel et al. 2003) are sufficient to rule out interpreting the transient X-ray source as a distant Be–star binary, while consistent with those of AXPs and SGRs.

The neutron star's own magnetic field is then a candidate to power the source's emission and dominate its spin-down. For a dipole magnetic field, the spin period and spin-down rate imply a characteristic magnetic field $B = 3.2\times10^{19}\sqrt{P\dot{P}} = 2.6\times10^{14}$ G and age $\tau = P/2\dot{P} \leq 7600$ yr. Such a super-critical field strength and relatively young pulsar age are typical of magnetars, which together with the aforementioned properties establish XTE J1810–197 as a new member of the class.

The transient behavior and long-term flux variability exhibited by the the source are uncommon properties of SGRs and AXPs. Only following a burst episode does the persistent flux show a comparable trend (e.g. SGR 1900+14: Woods et al. 2001; Ibrahim et al. 2001; Feroci et al. 2003, 1E 2259+586: Kaspi et al. 2003; Woods et al. 2003; and SGR 1627–41: Kouveliotou et al. 2003). The power-law index of the flux decay of the source (§ 2.3) falls within the range of those of SGRs (0.47-0.9), however, no SGR-like bursts were detected from the region by the PCA on 2002 November 17 or 2003 January 23. No PCA observations are available in between. With IPN, five bursts were recorded on 2002 December 5 and 6 (Hurley et al. 2002). One was localized to SGR 1806–20 by *Ulysses* and Konus-*Wind* but the others remain unlocalized. With the lack of PCA monitoring, a firm conclusion on a burst episode from the source during the intervening interval is difficult to reach, since weak and/or very soft SGR-like bursts can escape detection in γ–ray burst monitors (this was the case with 1E 2259+586 bursts that were only detected by the PCA; Kaspi et al. (2003)).

Alternatively, a quiescent outburst is viable in the magnetar model. Given that the magnetic field has to be greater than $B_0 \sim 2\times10^{14}(\theta_{max}/10^{-3})^{1/2}$ G to fracture the crust and induce burst activity (Thompson & Duncan 1995; θ_{max} is the crust yield strain), the energy associated with disturbances in $B < B_0$ may excite magnetospheric currents or dissipate in the crust, causing a sudden increase in the persistent flux followed by a long-lasting cooling phase.

The existence of transient magnetars bears important implications for magnetars and other classes of neutron stars. It suggests the presence of faint quiescent magnetars which have not been yet recognized as such. This would imply a larger population of magnetars than previously thought. Candidates are isolated radio-quiet neutron stars in states similar to that of XTE J1810–197 during the inactive *ASCA/ROSAT* phase. The identification of such a population has the potential of testing the hypothesis of a kinship between magnetars and other classes of objects such as the compact central objects in supernova remnants (Pavlov et al. 2004) and the dim isolated neutron stars (Haberl 2003).

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[1] $\dot{E} = I\Omega\dot{\Omega}$, where I is the moment of inertia of a canonical neutron star and $\Omega = 2\pi/P$

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